GEOLOGY

- **Geology** literally means "the study of Earth." The two broad areas of the science of geology are: (1) **physical geology**, which examines the materials composing Earth and the processes that operate beneath and upon its surface; and (2) **historical geology**, which seeks to understand the origin of Earth and its development through time.
- During the seventeenth and eighteen centuries, **catastrophism** influenced the formulation of explanations about Earth. Catastrophism states that Earth's landscapes have been developed primarily by great catastrophes. By contrast, **uniformitarianism**, one of the fundamental principles of modern geology advanced by ***James Hutton*** in the late 1700s states that the physical, chemical and biological laws that operate today have also operated in the geologic past. The idea is often summarized as "the present is the key to the past." Hutton argued that processes that appear to be slow-acting could, over long spans of time, produce effects that were just as great as those resulting from sudden catastrophic events. ***Sir Charles Lyell*** (mid-1800s) is given the most credit for advancing the basic principles of modern geology with the publication of the eleven editions of his great work, ***Principles of Geology***.
- Using the principles of **relative dating**, the placing of events in their proper sequence or order without knowing their absolute age in years, scientists developed a geologic time scale during the nineteenth century. Relative dates can be established by applying such principles as the ***law of superposition*** and the ***principle of faunal succession***.
- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. The process by which scientists gather facts and formulate scientific hypotheses and theories is called the **scientific method**. To determine what is occurring in the natural world, scientists often (1) collect facts, (2) develop a scientific hypothesis, (3) construct experiments to test the hypothesis, and (4) accept, modify or reject the hypothesis on the basis of extensive testing. Other discoveries represent purely theoretical ideas that have stood up to extensive examination. Still other scientific advancements have been made when a totally unexpected happening occurred during an experiment.
- Earth's physical environment is traditionally divided into three major parts: the solid Earth; the water portion of our planet, the **hydrosphere**; and Earth's gaseous envelope, the **atmosphere**. In addition, the **biosphere**, the totality of life on Earth,

interacts with each of the three physical realms and is n equally integral part of Earth.

- Two principal divisions of Earths surface are the continents and ocean basins. The **continental shelf** and **continental slope** mark the continent-ocean basin transition. Major continental features include mountains and shields. Important zones on the ocean floor are trenches and the extensive **oceanic ridge** system.
- The **nebular hypothesis** describes the formation of the solar system. The planets and Sun began forming about five billion years ago from a large cloud of dust and gases. As the cloud contracted, it began to rotate and assume a disk shape. Material that was gravitationally pulled toward the center became the **protosun**. Within the rotating disk, small centers, called **protoplanets**, swept up more and more of the cloud's debris. Because of their high temperatures and weak gravitational fields, the inner plates were unable to accumulate and retain many of the lighter components. Because of the very cold temperatures existing far from the Sun, the large outer planets consist of huge amounts of lighter materials. These gaseous substances account for the comparatively large sizes and low densities of the outer planets.
- The solid Earth has several subdivisions. Compositionally, it is divided into a thin outer crust, a solid rocky ***mantle***, and a dense ***core***. The core, in turn, is divided into a liquid outer core and a solid inner core. Two important mechanical layers are the **lithosphere** (rigid outer shell averaging about 100 kilometers in thickness) and the **asthenosphere** (a relatively weak layer located in the mantle beneath the lithosphere).
- The theory of **plate tectonics** provides a comprehensive model of Earth's internal workings. It holds that Earth's rigid outer lithosphere consists of several segments called **plates** that are slowly and continually in motion relative to each other. Most earthquakes, volcanic activity and mountain building are associated with the movements of these plates.
- The three distinct types of plate boundaries are (1) **divergent boundaries** – where plates move apart; (2) **convergent boundaries** – where plates move together causing one to go beneath the other, or where plates collide, which occurs when the leading edges are made of continental crust; and (3) **transform fault boundaries** – where plates slide past each other.
- Earth is a system consisting of many interacting parts that form a complex whole. The **rock cycle** is an excellent example of this idea and is a means of viewing

many of the interrelationships of geology. It illustrates the origin of the three basic rock types and the role of various geologic processes in transforming one rock type into another. **Igneous rock** forms from ***magma*** that cools and solidifies in a process called **crystallization**. **Sedimentary rock** forms when the products of weathering, called **sediment**, undergo ***lithification***. *Metamorphic rock* forms from rock that has been subjected to great pressure and heat in a process called **metamorphism**.

WEATHERING AND SOIL

- External processes that continually remove materials from higher elevations and move them to lower elevations include (1) **weathering** – the disintegration and decomposition of rock at or near Earth's surface; (2) **mass wasting** – the transfer of rock material downslope under the influence of gravity; and (3) **erosion** – the removal of material by a mobile agent, usually water, wind, or ice.
- **Mechanical weathering** is the physical breaking up of rock into smaller pieces. Rocks can be broken into smaller fragments by ***frost wedging*** (where water works its way into cracks or voids in rock, and upon freezing, expands and enlarges the openings), ***unloading*** (expansion and breaking due to a great reduction in pressure when the overlying rock is eroded away), ***thermal expansion*** (weakening of rock as the result of expansion and contraction as it heats and cools), and ***biological activity*** (by humans, burrowing animals, plant roots, etc.).
- **Chemical weathering** alters a rock's chemistry, changing it into different substances. Water is by far the most important agent of chemical weathering. ***Dissolution*** occurs when water-soluble minerals such as halite become dissolved in water. Oxygen dissolved in water will oxidize iron-rich minerals. When carbon dioxide (COs) is dissolved in water it forms ***carbonic acid***, which accelerates the decomposition of silicate minerals by ***hydrolysis***. The chemical weathering of silicate minerals frequently produces (1) soluble products containing sodium, calcium, potassium and magnesium ions, and silica in solution; (2) insoluble iron oxides; and (3) clay minerals.
- The rate at which rock weathers depends on such factors as (1) ***particle size*** – small pieces generally weather faster than large pieces; (2) ***mineral makeup*** – calcite readily dissolves in mildly acidic solutions, and silicate minerals that form first from magma are least resistant to chemical weathering ; and (3) ***climatic factors***, particularly temperature and moisture. Frequently, rocks exposed at

Earth's surface do not weather at the same rate. This ***differential weathering*** of rocks is influenced by such factors as mineral makeup, degree of jointing and exposure to the elements.

- **Soil** is a combination of mineral and organic matter, water and air – that portion of the ***regolith*** (the layer of rock and mineral fragments produced by weathering) that supports the growth of plants. About one-half of the total volume of a good-quality soil is a mixture of disintegrated and decomposed rock (mineral matter) and ***humus*** (the decayed remains of animal and plant life); the remaining half consists of pore spaces, where air and water circulate. The most important factors that control soil formation are ***parent material, time, climate, plants and animals,*** and ***slope*.**
- Soil-forming processes operate from the surface downward and produce zones or layers in the soil that are called horizons. From the surface downward, the soil horizons are respectively designated as ***O*** (largely organic matter), ***A*** (largely mineral matter), ***E*** (where the fine soil components and soluble materials have been removed by ***eluviation*** and ***leaching***), ***B*** (or ***subsoil***, often referred to as the ***zone of accumulation***), and ***C*** (partially altered parent material). Together the ***O*** and ***A*** horizons make up what is commonly called the **topsoil**.
- Although there are hundreds of soil types and sub-types worldwide, the three very generic types are (1) **pedalfer** – characterized by an accumulation of iron oxides and aluminum-rich clays in the B horizon; (2) **pedocal** – characterized by an accumulation of calcium carbonate; and (3) **laterite** – deep soils that develop in the hot, wet tropics that are poor for growing crops because they are highly leached.
- Soil erosion is a natural process; it is part of the constant recycling of Earth materials that we call the rock cycle. Once in a stream channel, soil particles are transported downstream and eventually deposited. ***Rates of soil erosion*** vary from one place to another and depend on the soil's characteristics as well as such factors as climate, slope and type of vegetation.

GEOLOGIC TIME

- The two types of dates used by geologists to interpret Earth history are (1) **relative dates**, which put events in their *proper sequence of formation*, and (2) **absolute dates**, which pinpoint the ***time in years*** when an event occurred.

- Relative dates can be established using the ***law of superposition*** (in an underformed sequence of sedimentary rocks or surface-deposited igneous rocks, each bed is older than the one above, and younger than the one below), ***principle of original horizontality*** (most layers are deposited in a horizontal position), ***principle of cross-cutting relationships*** (when a fault or intrusion cuts through another rock, the fault or intrusion is younger than the rocks cut through), and *inclusions* (the rock mass containing the inclusion is younger than the rock that provided the inclusion).
- **Unconformities** are gaps in the rock record. Each represents a long period during which deposition ceased, erosion removed previously formed rocks and then deposition resumed. The three basic types of unconformities are **angular unconformities** (tilted or folded sedimentary rocks that are overlain by younger, more flat-lying strata), **disconformities** (the strata on either side of the unconformity are essentially parallel), and **nonconformities** (where a break separates older metamorphic or intrusive igneous rocks from younger sedimentary strata).
- **Correlation**, the matching up of two or more geologic phenomena in different areas, is used to develop a geologic time scale that applies to the whole Earth.
- Fossils are used to correlate sedimentary rocks that are from different regions by using the rocks' distinctive fossil content and applying the ***principle of fossil succession***. The principle of fossil succession, which is based on the work of ***William Smith*** in the late 1700s, states that fossil organisms succeed one another in a definite and determinable order and therefore any time period can be recognized by its fossil content. The use of **index fossils,** those that are wide-spread geographically and are limited to a short span of geologic time, provides an important method for matching rocks of the same age.
- Each atom has a nucleus containing ***protons*** (positively charged particles) and ***neutrons*** (neutral particles). Orbiting the nucleus are negatively charged electrons. The **atomic number** of an atom is the number of protons in the nucleus. The **mass number** is the number of protons plus the number of neutrons in an atom's nucleus. **Isotopes** are variants of the same atom, but with a different number of neutrons, and hence a different mass number.
- *Radioactivity* is the spontaneous breaking apart (decay) of certain unstable atomic nuclei. Three common forms of radioactive decay are (1) emission of ***alpha***

particles from the nucleus, (2) emission of ***beta particles*** from the nucleus, and (3) ***capture of an electron*** by the nucleus.

- An unstable ***radioactive isotope***, called the **parent**, will decay and form ***daughter products***. The length of time for one-half of the nuclei of a radioactive isotope to decay is called the **half-life** of the isotope. Using a procedure called **radiometric dating**, if the half-life of the isotope is known, and the parent/daughter ratio can be measured, and the age of a sample can be calculated. An accurate radiometric date can only be obtained if the mineral containing the radioactive isotope remained in a closed system during the entire period since its formation.
- The **geologic time scale** divides Earth's history into units of varying magnitude. It is commonly presented in chart form, with the oldest time and even at the bottom and the youngest at the top. The principle subdivisions of the geologic time scale, called **eons**, include the ***Hadean, Archean, Proterozoic*** (together, these three eons are commonly referred to as the ***Precambrian***), and beginning about 570 million years ago, the ***Phanerozoic***. The Phanerozoic (meaning "visible life") eon is divided into the following eras: **Paleozoic** ("ancient life"), **Mesozoic** ("middle life") and **Cenozoic** ("recent life").
- One problem in assigning absolute dates is that ***not all rocks can be radiometrically dated***. A sedimentary rock may contain particles of many ages that have been weathered from different rocks that formed at various times. One way geologists assign absolute dates to sedimentary rocks is to relate them to datable igneous masses, such as volcanic ash beds.

MASS WASTING

- **Mass wasting** refers to the downslope movement of rock, regolith and soil under the direct influence of gravity. In the evolution of most landforms, mass wasting is the step that follows weathering. The combined effects of mass wasting and erosion by running water produce stream valleys.
- ***Gravity is the controlling force of mass wasting***. Other factors that play an important role in overcoming inertia and triggering downslope movements are saturation of the material with water and over-steepening of slopes beyond the ***angle of repose***.
- The various processes included under the name of mass wasting are divided and described on the basis of (1) the type of material involved (debris, mud, earth, or

rock); (2) the type of motion (fall, slide, or flow); and (3) the rate of movement (rapid or slow).

- The more rapid forms of mass wasting include **slump**, the downward sliding of a mass of rock or unconsolidated material moving as a unit along a curved surface; **rockslide**, blocks of bedrock breaking loose and sliding downslope; **debris flow**, a relatively rapid flow of soil and regolith containing a large amount of water; and **earthflow**, an unconfined flow of saturated, clay-rich soil that most often occurs on a hillside in a humid area following heavy precipitation or snowmelt.
- The slowest forms of mass wasting include **creep**, the gradual downhill movement of soil and regolith, and **solifluction**, a form of mass wasting that is common in regions underlain by **permafrost** (permanently frozen ground associated with tundra and ice cap climates).

RUNNING WATER

- The **hydrologic cycle** describes the continuous interchange of water among the oceans, atmosphere and continents. Powered by energy from the Sun, it is a global system in which the atmosphere provides the link between the oceans and continents. The processes involved in the hydrologic cycle include ***precipitation, evaporation, infiltration*** (the movement of water into rocks or soil through cracks and pore spaces), ***runoff*** (water that flows over the land) and ***transpiration*** (the release of water vapor to the atmosphere by plants). Running water is the single most important agent sculpturing Earth's land surface.
- The amount of water running off the land rather than sinking into the ground depends upon the ***infiltration capacity*** of the soil. Initially, runoff flows as broad, thin sheets across the ground, appropriately termed **sheet flow**. After a short distance, threads of current typically develop and tiny channels called **rills** form.
- The factors that determine a stream's velocity are ***gradient*** (slope of the stream channel), ***cross-sectional shape, size*** and ***roughness*** of the channel and the stream's ***discharge*** (the amount of water passing a given point per unit of time, frequently measured in cubic meters or cubic feet per second). Most often, the gradient and roughness of a stream decrease downstream, while width, depth, discharge and velocity increase.
- The two general types of base level (the lowest point to which a stream may erode its channel) are: (1) **ultimate base level** (sea level) and (2*)* **temporary**, or **local**, **base level**. Any change in base level will cause a stream to adjust and establish a

new balance. Lowering base level will cause a stream to erode, whereas raising base level results in deposition of material in the channel.

- Streams transport their load of sediment in solution (***dissolved load***), in suspension (***suspended load***), and along the bottom of the channel **(*bed load*)**. Much of the dissolved load is contributed by groundwater. Most streams carry the greatest part of the load in suspension. The bed load moves only intermittently and usually represents the smallest portion of a stream's load.
- A stream's ability to transport solid particles is described using two criteria: ***capacity*** (the maximum load of solid particles a stream can carry) and ***competence*** (the maximum particle size a stream can transport). Competence increases as the square of stream velocity, so if velocity doubles, water's force increases fourfold.
- Streams deposit sediment when velocity slows and competence is reduced. This result in **sorting**, the process by which like-sized particles are deposited together. Stream deposits are called **alluvium** and may occur as channel deposits called *bars*, as floodplain deposits, which include ***natural levees*** and as ***deltas*** or ***alluvial fans*** at the mouths of streams.
- Although many gradations exist, the two general types of stream valleys are (1) ***narrow V-shaped valleys*** and (2) ***wide valleys with flat floors***. Because the dominant activity is downcutting toward base level, narrow valleys often contain ***waterfalls*** and ***rapids***. When a stream has cut its channel closer to base level, its energy is directed from side-to-side, and erosion produces a flat valley floor, or **floodplain**. Streams that flow upon floodplains often move in sweeping bends called **meanders**. Widespread meandering may result in shorter channel segments, called **cutoffs** and/or abandoned bends, called **oxbow lakes**.
- The land area that contributes water to a stream is called a **drainage basin**. Drainage basins are separated by an imaginary line called a **divide**. Common drainage patterns (the form of a network of stream) produced by a main channel and its tributaries include (1) ***dendritic***, (2) ***radial***, (3) ***rectangular*** and (4) ***trellis***.
- ***Headward erosion*** lengthens a stream course by extending the head of its valley upslope. This process can lead to ***stream piracy*** (the diversion of the drainage of one stream by another). Former water gaps called **wind gaps** can result from stream piracy.
- **Floods** are triggered by heavy rains and/or snowmelt. Sometimes human interference can worsen or even cause floods. Flood-control measures include the building of artificial levees and dams, as well as ***channelization***, which could

involve creating **artificial cutoffs**. Many scientists and engineers advocate a nonstructural approach to flood control that involves more appropriate land use.

GROUNDWATER

- As a resource, **groundwater** represents the largest reservoir of freshwater that is readily available to humans. Geologically, the dissolving action of groundwater produces **caves** and **sinkholes**. Groundwater is also an equalizer of stream flow.
- Groundwater is that water which completely fills the pore spaces in sediment and rock in the sub-surface **zone of saturation**. The upper limit of this zone is the water table. The zone of aeration is above the water table where the soil, sediment and rock are not saturated.
- Materials with very small pore spaces (such as clay) hinder or prevent groundwater movement and are called **aquitards**. **Aquifers** consist of materials with larger pore spaces (such as sand) that are permeable and transmit groundwater freely.
- Groundwater moves in looping curves that are a compromise between the downward pull of gravity and the tendency of water to move toward areas of reduced pressure.
- **Springs** occur whenever the water table intersects the land surface and a natural flow of groundwater results. **Wells**, openings bored into the zone of saturation, withdraw groundwater and create roughly conical depressions in the water table known as **cones of depression**. **Artesian wells** occur when water rises above the level at which it was initially encountered.
- When groundwater circulates at great depths, it becomes heated. If it rises, the water may emerge as a **hot spring**. **Geysers** occur when groundwater is heated in underground chambers, expands and some water quickly changes to steam, causing the geyser to erupt. The source of heat for most hot springs and geysers is hot igneous rock.
- Some of the current environmental problems involving groundwater include (1) overuse by intense irrigation, (2) land subsidence caused by groundwater withdrawal, (3) saltwater contamination, and (4) contamination by pollutants.
- Most **caverns** form in limestone at or below the water table when acidic groundwater dissolves rock along lines of weakness, such as joints and bedding planes. The various **dripstone** features found in caverns are collectively called **speleotherms**. Landscapes that to a large extent have been shaped by the

dissolving power of groundwater exhibit **karst topography**, an irregular terrain punctuated with many depressions, called **sinkholes** or **sinks**.

GLACIERS AND GLACIATION

- A **glacier** is a thick mass of ice originating on land as a result of the compaction and recrystallization of snow and it shows evidence of past or present flow. Today, **valley** or **alpine glaciers** are found in mountain areas where they usually follow valleys that were originally occupied by streams. **Ice sheets** exist on a much larger scale, covering most of Greenland and Antarctica.
- Near the surface of a glacier, in the ***zone of fracture***, ice is brittle. However, below about 50 meters, pressure is great, causing ice to ***flow*** like ***plastic material***. A second important mechanism of glacial movement consists of the entire ice mass ***slipping*** along the ground.
- The average velocity of glacial movement is generally quite slow, but varies considerably from one glacier to another. The advance of some glaciers is characterized by periods of extremely rapid movements called **surges**.
- Glaciers form in areas where more snow falls in winter than melts during summer. Snow accumulation and ice formation occur in the ***zone of accumulation***. Its outer limits are defined by the snowline. Beyond the snowline is the zone of wastage, where there is a net loss to the glacier. The **glacial budget** is the balance, or lack of balance, between accumulation at the upper end of the glacier, and loss, called **ablation**, at the lower end.
- Glaciers erode land by ***plucking*** (lifting pieces of bedrock out of place) and **i** (grinding and scraping of a rock surface). Erosional features produced by valley glaciers include glacial troughs, hanging valleys, pater noster lakes, fiords, cirques, arêtes, horns and roches moutonnees.
- Any sediment of glacial origin is called **drift**. The two distinct types of glacial drift are (1) **till**, which is material deposited directly by the ice; and (2) stratified **drift**, which is sediment laid down by meltwater from a glacier.
- The most widespread features created by glacial deposition are layers or ridges of till, called **moraines**. Associated with valley glaciers are ***lateral moraines***, formed along the sides of the valley, and ***medial moraines***, formed between two valley glaciers that have joined. ***End moraines***, which mark the former position of the front of a glacier and ***ground moraines***, undulating layers of till deposited as the ice front retreats, are common to both valley glaciers and ice sheets. An **outwash**

plain is often associated with the end moraine of an ice sheet. A **valley train** may form when the glacier is confined to a valley. Other depositional features include ***drumlins*** (streamlined asymmetrical hills composed of till), ***eskers*** (sinuous ridges composed largely of sand and gravel deposited by streams flowing in tunnels beneath the ice, near the terminus of a glacier), and ***kames*** (steep-sided hills consisting of sand and gravel).

- The **Ice Age**, which began about two million years ago, was a very complex period characterized by a number of advances and withdrawals of glacial ice. Most of the major glacial episodes occurred during a division of the geologic time scale called the **Pleistocene epoch**. Perhaps the most convincing evidence for the occurrence of several glacial advances during the Ice Age is the widespread existence of ***multiple layers of drift*** and an uninterrupted record of climate cycles preserved in ***seafloor sediments***.
- In addition to massive erosional and depositional work, other effects of Ice Age glaciers included the ***forced migration of organisms, changes in stream courses, adjustment of the crust*** by rebounding after the removal of the immense load of ice and climate changes caused by the existence of the glaciers themselves. In the sea, the most far-reaching effect of the Ice Age was the ***worldwide change*** in ***sea level*** that accompanied each advance and retreat of the ice sheets.
- Any theory that attempts to explain the causes of glacial ages must answer two basic questions: (1) What causes the onset of glacial conditions? and (2) What caused the alternating glacial and interglacial stages that have been documented for the Pleistocene epoch? Two of the many hypotheses for the cause of glacial ages involve (1) plate tectonics and (2) variations in Earth's orbit.

DESERTS AND WINDS

- The **concept of dryness is relative**; it refers to any situation in which a water deficiency exists. Dry regions encompass about 30 percent of Earth's land surface. Two climatic types are commonly recognized: **desert**, which is arid and **steppe** (a marginal and more humid variant of desert), which is semi-arid. ***Low-latitude deserts*** coincide with the zones of subtropical highs in lower latitudes. On the other hand, ***middle-latitude deserts*** exist principally because of their positions in the deep interiors of large landmasses far removed from the ocean.
- The same geologic processes that operate in humid regions also operate in deserts, but under contrasting climatic conditions. In dry lands rock weathering of any type

is greatly reduced because of the lack of moisture and the scarcity of organic acids from decaying planets. Much of the weathered debris in deserts is the result of **mechanical weathering.** Practically all desert streams are dry most of the time and are said to be **ephemeral**. Stream courses in deserts are seldom well integrated and lack an extensive system of tributaries. Nevertheless, running water is responsible for most of the erosional work in a desert. Although wind erosion is more significant in dry areas than elsewhere, the main role of wind in a desert is in the transportation and deposition of sediment.

- Because arid regions typically lack permanent streams, they are characterized as having ***interior drainage***. Many of the landscapes of the Basin and Range region of the western and southwestern United States are the result of streams eroding uplifted mountain blocks and depositing the sediment in interior basins. ***Alluvial fans, playas*** and ***playa lakes*** are features often associated with these landscapes. In the late stages of erosion, the mountain areas are reduced to a few large bedrock knobs, called **inselbergs**, projecting above sediment-filled basins.
- The transport of sediment by wind differs from that by running water in two ways. First, wind has a low density compared to water; thus, it is not capable of picking up and transporting coarse materials. Second, because wind is not confined to channels, it can spread sediment over large areas. The **bed load** of wind consists of sand grains skipping and bouncing along the surface in a process termed saltation. Fine dust particles are capable of being carried by the wind great distances as **suspended load**.
- Compared to running water and glaciers, wind is a relatively insignificant erosional agent. **Deflation**, the lifting and removal of loose material, often produces shallow depressions called **blowouts**. In portions of many deserts the surface is a layer of coarse pebbles and gravels, called **desert pavement**, too large to be moved by the wind. Wind also erodes by ***abrasion***, often creating interestingly shaped stones called **ventifacts**. Because sand seldom travels more than a meter above the surface, the effect of abrasion is obviously limited in vertical extent.
- Wind deposits are of two distinct types: (1**)** ***mounds and ridges of sand***, called **dunes**, which are formed from sediment that is carried as part of the wind's bed load; and (2) extensive ***blankets of silt***, called **loess**, that once were carried by wind in suspension. The profile of a dune shows an asymmetrical shape with the leeward (sheltered) slope being steep and the windward slope more gently

inclined. The types of sand dunes include (1) barchan dunes; (2) transverse dunes; (3) barchanoid dunes; (4) longitudinal dunes; (5) parabolic dunes; and (6) star dunes. The thickest and most extensive deposits of loess occur in western and northern China. Unlike the deposits in China, which originated in deserts, the loess in the United States and Europe is an indirect product of glaciation.

SHORELINES

- The three factors that influence **the *height, wavelength*** and ***period*** of a wave are (1) wind speed, (2) length of time the wind has blown, and (3) fetch, the distance that the wind has traveled across the open water.
- The two types of wind-generated waves are (1) **waves of oscillation**, which are waves in the open sea in which the wave form advances as the water particles move in circular orbits, and (2) **waves of translation**, the turbulent advance of water formed near the shore as waves of oscillation collapse, or break, and form **surf**.
- Wave erosion is caused by ***wave impact pressure*** and ***abrasion*** (the sawing and grinding action of water armed with rock fragments). The bending of waves is called **wave refraction**. Owing to refraction, wave impact is concentrated against the sides and ends of headlands.
- Most waves reach the shore at an angle. The uprush (swash) and backwash of water from each breaking wave moves the sediment in a zigzag pattern along the beach. This movement, called **beach drift**, can transport sand hundreds or even thousands of meters each day. Oblique waves also produce ***longshore currents*** within the surf zone that flow parallel to the shore.
- Features produced by **shoreline erosion** include ***wave-cut cliffs*** (which originate from the cutting action of the surf against the base of coastal land), ***wave-cut platforms*** (relatively flat, benchkike surfaces left behind by receding cliffs), ***sea arches*** (formed when a headland is eroded and two caves from opposite sides unite), and ***sea stacks*** (formed when the roof of a sea arch collapses).
- Some of the depositional features formed when sediment is moved by beach drift and longshore currents are **spits** (elongated ridges of sand that project from the land into the mouth of an adjacent bay), **baymouth bars** (sand bars that completely cross a bay), and **tombolos** ridges of sand that connect an island to the mainland or to another island). Along the Atlantic and Gulf Coastal Plains, the

shore zone is characterized by ***barrier islands***, low ridges of sand that parallel the coast at distances from 3 to 30 kilometers offshore.

- Local factors that influence shoreline erosion are (1) the proximity of a coast to sediment-laden rivers, (2) the degree of tectonic activity, (3) the topography and composition of the land, (4) prevailing winds and weather patterns, and (5) the configuration of the coastline and nearshore areas.
- Three basic responses to shoreline erosion problems are (1) building ***structures*** such as ***groins*** (short walls built at a right angle to the shore to trap moving sand), breakwaters (structures built parallel to the shoreline to protect it from the force of large breaking waves), and ***seawalls*** (barriers constructed to prevent waves from reaching the area behind the wall) to hold the shoreline in place; (2) ***beach nourishment***, which involves the addition of sand to replenish eroding beaches; and (3) ***relocating*** buildings away from the beach.
- Because of basic geological differences, the nature of shoreline erosion problems along America's Pacific and Atlantic coasts is very different. Much of the development along the Atlantic and Gulf coasts has occurred on barrier islands, which receive the full force of major storms. Much of the Pacific Coast is characterized by narrow beaches backed by steep cliffs and mountain ranges. A major problem facing the Pacific shoreline is a narrowing of beaches caused because the natural flow of materials to the coast has been interrupted by dams built for irrigation and flood control.
- One frequency used classification of coasts is based upon changes that have occurred with respect to sea level. **Emergent coasts**, often with wave-cut cliffs and wave-cut platforms above sea level, develop either because an area experiences uplift or as a result of a drop in sea level. Conversely, **submergent coasts**, with their drowned river mouths, called **estuaries**, are created when sea level rises or the land adjacent to the sea subsides.
- **Tides**, the daily rise and fall in the elevation of the ocean surface, are caused by the ***gravitational attraction*** of the Moon and to a lesser extent, by the Sun. Near the times of new and full moons, the Sun and Moon are aligned, and their gravitational forces are added together to produce especially high and low tides. These are called the **spring tides**. Conversely, at about the times of the first and third quarters of the Moon, when the gravitational forces of the Moon and Sun are at right angles, the daily tidal range is less. These are called **neap tides**.

- **Tidal currents** are horizontal movements of water that accompany the rise and fall of tides. **Tidal flats** are the areas that are affected by the advancing and retreating tidal currents. When tidal currents slow after emerging from narrow inlets, they deposit sediment that may eventually create **tidal deltas**.

CRUSTAL DEFORMATION

- **Deformation** refers to changes in the volume and/or shape of a rock body and is most pronounced along plate margins. **Stress** is a measure of the amount of force that causes rocks to deform, whereas **strain** is the change (deformation) caused by stress. Stress that is uniform in all directions is called **confining pressure**, whereas **differential stresses** are applied unequally in different directions. Differential stresses that shorten a rock body are **compressional stresses**; those that elongate a rock unit are **tensional stresses**.
- Rocks deform differently depending on their chemical makeup, environment and the rate at which stress is applied. Rocks first respond by deforming elastically, and will return to their original shape when the stress is removed. Once the elastic limit is surpassed, rocks either deform plastically or they fracture. Plastic deformation changes the shape of a rock unit through folding and flowing and the rock is said to behave in a ductile manner. **Plastic deformation** occurs in a high temperature/high pressure environment. In a near-surface environment, when stress is applied rapidly, most rocks deform by *brittle failure*.
- The orientation of rock units or fault surfaces is established with measurements called strike and dip. **Strike** is the compass direction of a line produced by the intersection of an inclined rock layer or fault with a horizontal plane. **Dip** is the angle of inclination of the surface of a rock unit or fault measured from a horizontal plane.
- The most basic geologic structures associated with rock deformation are folds (flat-lying sedimentary and volcanic rocks bent into a series of wavelike undulation) and **faults**. The two most common types of folds are **anticlines**, formed by the upfolding, or arching, of rock layers and **synclines**, which are downfolds. Most folds are the result of horizontal compressional stresses. Folds can be symmetrical, asymmetrical, or, if one limb has been tilted beyond the vertical, overturned. **Domes** (upwarped structures) and **basins** (downwarped structures) are circular or somewhat elongated folds formed by vertical displacements of strata.

- Faults are fractures in the crust along which appreciable displacement has occurred. Faults in which the movement is primarily vertical are called **dip-slip faults**. Dip-slip faults include both **normal** and **reverse faults**. Low-angle reverse faults are called **thrust faults**. Normal faults indicate tensional stresses that pull the crust apart. Along the spreading centers of plates, divergence can cause a central block called a **graben**, bounded by normal faults, to drop as the plate separate.
- Reverse and thrust faulting indicate that ***compressional forces*** are at work. Large **thrust faults** are found along subduction zones and other convergent boundaries where plates are colliding. In mountainous regions such as the Alps, Northern Rockies, Himalayas and Appalachians, thrust faults have displaced strata as far as 50 kilometers over adjacent rock units.
- **Strike-slip faults** exhibit mainly horizontal displacement parallel to the strike of the fault surface. Large strike-slip faults, called **transform faults**, accommodate displacement between plate boundaries. Most transform faults cut the oceanic lithosphere and link spreading centers. The San Andreas fault cuts the continental lithosphere and accommodates the northward displacement of southwestern California.
- **Joints** are fractures along which no appreciable displacement has occurred. Joints generally occur in groups with roughly parallel orientations. Most joints are the result of brittle failure of rock units located in the outermost crust.

EARTHQUAKES

- **Earthquakes** are vibrations of Earth produced by the rapid release of energy from rocks that rupture because they have been subjected to stresses beyond their limit. This energy, which takes the form of waves, radiates in all directions from the earthquake's source, called the **focus**. The movements that produce most earthquakes occur along large fractures, called **faults** that are usually associated with plate boundaries.
- Along a fault, rocks store energy as they are bent. As slippage occurs at the weakest point (the focus), displacement will exert stress farther along a fault, where additional slippage will occur until most of the built-up strain is released. An earthquake occurs as the rock elastically returns to its original shape. The "springing back" of the rock is termed **elastic rebound**. Small earthquakes, called

foreshocks, often precede a major earthquake. The adjustments that follow a major earthquake often generate smaller earthquakes called **aftershocks**.

- Two main types of seismic waves are generated during an earthquake: (1) **surface waves**, which travel along the outer layer of Earth; and (2) **body waves**, which travel through Earth's interior. Body waves are further divided into ***primary***, or ***P waves***, which push (compress) and pull (expand) rocks in the direction the wave is traveling, and ***secondary*** or **S waves**, which "shake" the particles in rock at right angles to their direction of travel. P waves can travel through solids, liquids and gases. Fluids (gases and liquids) will not transmit S waves. In any solid material, P waves travel about 1.7 times faster than do S waves.
- The location on Earth's surface directly above the focus of an earthquake is the **epicenter**. An epicenter is determined using the difference in velocities of P and S waves. Using the difference in arrival times between P and S waves, the distance separating a recording station from the earthquake can be determined. When the distances are known from three or more seismic stations, the epicenter can be located using a method called **triangulation**.
- A close relation exists between earthquake epicenters and plate boundaries. The principal earthquake epicenter zones are along the outer margin of the Pacific Ocean, known as the **circum-Pacific belt**, and through the world's oceans along the ***oceanic ridge system***.
- Earthquake ***intensity*** depends not only on the strength of the earthquake but also on other factors, such as distance from the epicenter, the nature of surface materials, and building design. The **Mercalli intensity scale** assesses the damage from a quake at a specific location. Using the **Richter scale**, the magnitude (a measure of the total amount of energy released) of an earthquake is determined by measuring the ***amplitude*** (maximum displacement) of the largest seismic wave recorded. A logarithmic scale is used to express magnitude, in which a tenfold increase in recorded wave amplitude corresponds to an increase of 1 on the magnitude scale. Each unit of Richter magnitude equates to roughly a 32-fold energy increase.
- The most obvious factors determining the amount of destruction accompanying an earthquake are the magnitude of the earthquake and the proximity of the quake to a populated area. Structural damage attributable to earthquake vibrations depends on several factors, including (1) wave amplitudes, (2) the duration of the vibrations, (3) the nature of the material upon which the structure rests, and (4) the

design of the structure. Secondary effects of earthquakes include tsunamis, landslides, ground subsidence and fire.

- Substantial research to predict earthquakes is underway in Japan, the United States, China and Russia – countries where earthquake risk is high. No reliable method of short-range prediction has yet been devised. Long-range forecasts are based on the premise that earthquakes are repetitive or cyclical. Seismologists study the history of earthquakes, for patterns, so their occurrences might be predicted. Long-range forecasts are important because they provide information used to develop the Uniform Building Code and assist in land-use planning.

EARTH'S INTERIOR

- Much of our knowledge of Earth's interior comes from the study of earthquake waves that penetrate Earth and emerge at some distant point. In general, seismic waves travel faster in solid elastic materials and slower in weaker layers. Further, seismic energy is reflected and refracted (bent) at boundaries between compositionally or mechanically different materials. By carefully measuring the travel times of seismic waves, seismologists have been able to determine the major divisions of Earth's interior.
- The principal compositional layers of Earth include (1) the crust, Earth's comparatively thin outer skin that ranges in thickness from 3 kilometers (2 miles) at the oceanic ridges to over 70 kilometers (40 miles) in some mountainous belts such as the Andes and Himalayas; (2) the **mantle**, a solid rocky shell that extends to a depth of about 2900 kilometers (1800 miles); and (3) the **core**, an iron-rich sphere having a radius of 3486 kilometers (2166 miles).
- The crust, the rigid outermost layer of Earth, is divided into oceanic and continental crust. Oceanic crust ranges from 3 to 15 kilometers in thickness and is composed of basaltic igneous rocks. By contrast, the continental crust consists of a large variety of rock types having an average composition of felsic rock called granodiorite. The rocks of the oceanic crust are younger (180 million years or less) and more dense (about 3.0 g/cm^3) than continental rocks. Continental rocks have an average density of about 2.7 g/cm^3 and some have been discovered that exceed 3.8 billion years in age.
- Over 82 percent of Earth's volume is contained in the mantle, a rocky shell about 2900 kilometers thick. The boundary between the crust and mantle represents a change in composition. Although the mantle behaves like a solid when

transmitting earthquake waves, mantle rocks are able to flow at an infinitesimally slow rate. Some of the rocks in the lowermost mantle (D” layer) are thought to be partially molten.

- The core is composed mostly of iron with lesser amounts of nickel and other elements. At the extreme pressure found in the core, this iron-rich material has an average density of about 11 g/cm^3 and approaches 14 times the density of water at Earth’s center. The inner and outer core are compositionally similar; however, the outer core is liquid and capable of flow. It is the circulation within the core of our rotating planet that generates Earth’s magnetic field.
- Earth’s outer layer, including the uppermost mantle and crust, form a relatively cool, rigid shell known as the **lithosphere** (sphere of rock). Averaging about 100 kilometers in thickness, the lithosphere may be 250 kilometers or more in thickness below older portions (shields) of the continents. Within the ocean basins the lithosphere ranges from a few kilometers thick along the oceanic ridges to perhaps 100 kilometers in regions of older and cooler crustal rocks.
- Beneath the lithosphere (to a depth of about 660 kilometers) lies a soft, relatively weak layer located in the upper mantle known as the **asthenosphere** (“weak sphere”). The upper 150 kilometers or so of the asthenosphere has a temperature/pressure regime in which a small amount of melting takes place (perhaps 1 to 5 percent). Within this very weak zone, the lithosphere is effectively detached from the asthenosphere located below.
- Temperature gradually increases with depth in our planet’s interior. Three processes contribute to Earth’s internal heat: (1) heat emitted by radioactivity; (2) heat released as iron solidifies in the core; and (3) heat released by colliding particles during the formative years of our planet.
- Convective flow in the mantle is thought to consist of buoyant plumes of hot rocks and downward flow of cool, dense slabs of lithosphere. This thermally generated convective flow is the driving force that propels lithospheric plates across the globe.

OCEAN FLOOR AND SEAFLOOR SPREADING

- Ocean depths are determined using an **echo sounder**, a device carried by a ship that bounces sound off the ocean floor. The time it takes for the sound waves to make the round trip to the bottom and back to the ship is directly related to the depth. Continuous data from the echoes are plotted to produce a profile of the ocean floor. Although much of the ocean floor has been mapped using echo sounder, only the large topographic features are shown.

- Oceanographers studying the topography of the ocean basins have delineated three major units: ***continental margins, deep ocean basins*** and ***mid-ocean ridges***.
- The zones that collectively make up a passive continental margin include the **continental shelf** (a gently sloping, submerged surface extending from the shoreline toward the deep-ocean basin); **continental slope** (the true edge of the continent, which a steep slope that leads from the continental shelf into deep water); and in regions where trenches do not exist, the steep continental slope merges into a more gradual incline known as the **continental rise**. The continental rise consists of sediments that have moved downslope from the continental shelf to the deep-ocean floor.
- **Active continental margins** are located primarily around the Pacific Ocean in areas where the leading edge of a continent is overrunning oceanic lithosphere. Here sediment scraped from the descending oceanic plate is plastered against the continent to form a collection of sediments called an **accretionary wedge**. An active continental margin generally has a narrow continental shelf, which grades into a deep-ocean trench.
- **Submarine canyons** are deep, steep-sided valleys that originate on the continental slope and may extend to depths of 3 kilometers. Some of these canyons appear to be the seaward extensions of river valleys. However, most information seems to favor the view that many submarine canyons are excavated by **turbidity currents** (downslope movements of dense, sediment-laden water). **Turbidites**, sediments deposited by turbidity currents are characterized by a decrease in sediment grain size from bottom to top, a phenomenon known as **graded bedding.**
- The deep ocean basin lies between the continental margin and the mid-ocean ridge system. Its features include ***deep-ocean trenches*** (long, narrow depressions that are the deepest parts of the ocean and where moving crustal plates descend back into the mantle); ***abyssal plains*** (among the most level places on Earth, consisting of thick accumulations of sediments that were deposited atop the low, rough portions of the ocean floor by turbidity currents); and ***seamounts*** (isolated, steep-sided volcanic peaks on the ocean floor that originate near oceanic ridges or in association with volcanic hot spots).
- **Coral reefs,** which are confined largely to the warm, sunlit waters of the Pacific and Indian oceans, are constructed over thousands of years primarily from the

accumulation of skeletal remains and secretions of corals and certain algae. A coral island, called an **atoll**, consists of a continuous or broken ring of coral reef surrounding a central lagoon. Atolls form from corals that grow on the flanks of sinking volcanic islands, where the corals continue to build the reef complex upward as the island slowly sinks.

- There are three broad categories of seafloor sediments. **Terrigenous sediment** consists primarily of mineral grains that were weathered from continental rocks and transported to the ocean. **Biogenous sediment** consists of shells and skeletons of marine animals and plants. **Hydrogenous sediment** includes minerals that crystallize directly from seawater through various chemical reactions.
- **Mid-ocean ridges**, the sites of seafloor spreading, are found in all major oceans and represent more than 20 percent of Earth's surface. These broad features are certainly the most prominent features in the oceans, for they form an almost continuous mountain range. Ridges are characterized by an elevated position, extensive faulting and volcanic structures that have developed on newly formed oceanic crust. Most of the geologic activity associated with ridges occurs along a narrow region on the ridge crest, called the **rift zone**, where magma from the asthenosphere moves upward to create new slivers of oceanic crust.
- New oceanic crust is formed in a continuous manner by the process of seafloor spreading. The upper crust is composed of **pillow lavas** of basaltic composition. Underlying this layer are numerous interconnected dikes (***sheeted dikes***) that are connected to a layer of gabbro. This entire sequence of rock is called an **ophiolite complex.**

PLATE TECTONICS

- In the early 1900s ***Alfred Wegener*** set forth the **continental drift** hpothesis. One of its major tenets was that a supercontinent called **Pangaea** began breaking apart into smaller continents about 200 million years ago. The smaller continental fragments then drifted to their present positions. To support the claim that the now-separate continents were once joined, Wegener and others used the fit of South America and Africa, fossil evidence, rock types and structures and ancient climates. On of the main objections to the continental drift hypothesis was its inability to provide an acceptable mechanism for the movement of continents.
- From the study of **paleomagnetism,** researchers learned that the continents had wandered as Wegener proposed. In 1962, Harry Hess formulated the idea of **seafloor spreading**, which states that new seafloor is continually being generated at mid-oceanic ridges and old, dense seafloor is being consumed at the deep ocean

trenches. Support for seafloor spreading followed, with the discovery of alternating stripes of high and low-intensity magnetism that parallel the ridge crests.

- By 1968, continental drift and seafloor spreading were united into a far more encompassing theory known as **plate tectonics**. According to plate tectonics, Earth's rigid outer layer (lithosphere) overlies a weaker region called the **asthenosphere**. Further, the lithosphere is broken into seven large and numerous smaller segments called **plates** that are in motion and continually changing in shape and size. Plates move as relatively coherent units and are deformed mainly along their boundaries.
- **Divergent plate boundaries** occur where plates move apart, resulting in upwelling of material from the mantle to create new seafloor. Most divergent boundaries occur along the axis of the oceanic ridge system and are associated with seafloor spreading., which occurs at rates of 2 to 20 centimeters per year. New divergent boundaries may form within a continent (for example, the East African Rift Valleys) where they may fragment a landmass and develop a new ocean basin.
- **Convergent plate boundaries** occur where plates move together, resulting in the subduction (consumption) of oceanic lithosphere into the mantle along a deep oceanic trench. Convergence between an oceanic and continental block results in subduction of the oceanic slab and the formation of a **continental volcanic arc** such as the Andes of South America. Oceanic-oceanic convergence results in an arc-shaped chain of volcanic islands called a **volcanic island arc**. When two plates carrying continental crust converge, both plates are too buoyant to be subducted. The result is a "collision" resulting in the formation of a mountain belt such as the Himalayas.
- **Transform fault boundaries** occur where plates grind past each other without the production or destruction of lithosphere. Most transform faults join two segments of a mid-oceanic ridge. Others connect spreading centers to subduction zones and thus facilitate the transport of oceanic crust created at a ridge crest to its site of destruction, at a deep ocean trench. Still other, like the San Andreas fault, cut through continental crust.
- The theory of plate tectonics is supported by (1) the global distribution of **earthquakes** and their close association with plate boundaries; (2) the ages and thickness of **sediments** from the floors of the deep-ocean basins; and (3) the existence of island chains that formed over **hot spots** and provide a frame of reference for tracing the direction of plate motion.

- The gross details of the migrations of individual continents over the past billion years have been reconstructed. Pangaea began breaking apart about 200 million years ago. North America separated from Africa between 200 million and 165 million years ago. Prior to the formation of Pangaea the landmasses had gone through several episodes of fragmentation similar to what we see happening today.
- Several models for the driving mechanism of plates have been proposed. One model, the ***convection current hypothesis***, involves various **convection cells** within the mantle that carry the overlying plates like packages on a conveyor belt. The ***slab-pull hypothesis*** proposes that when cold, dense oceanic material is subducted it pulls the trailing lithosphere along. **Slab-push** may occur when gravity sets the elevated slabs astride the ridge crest in motion. Another model suggests that relatively narrow ***hot plumes*** of rock within the mantle contribute to plate motion. No single driving mechanism can account for all major facets of plate motion.

MOUNTAIN BUILDING AND THE EVOLUTION OF CONTINENTS

- The name for the processes that collectively produce a mountain system is **orogenesis**. Earth's less dense crust floats on top of the denser and deformable rocks in the mantle, much like wooden blocks floating in water. This concept of a floating crust in gravitational balance is called **isostasy**. Most mountains are located where the crust has been shortened and thickened. Therefore, mountains have deep crustal roots that support them. As erosion lowers the peaks, isostatic adjustment gradually raises the mountains in response. The processes of uplifting and erosion will continue until the mountain block reaches "normal" crustal thickness. Mountains can also rise where hot rising magma upwards the overlying crust.
- Most mountains consist of roughly parallel ridges of folded and faulted sedimentary and volcanic rocks, portions of which have been strongly metamorphosed and intruded by younger igneous bodies.
- Major mountain systems form along ***convergent plate boundaries***. **Andean-type mountain building** along the continental margins involves the convergence of an oceanic plate and a plate whose leading edge contains continental crust. At some point in the formation of Andean-type mountains a **subduction zone** forms along with a ***continental volcanic arc***. Sediment from the land, as well as material scraped from the subducting plate, becomes plastered against the landward side of the trench, forming an ***accretionary wedge***. One of the best examples of an

inactive Andean-type mountain belt is found in the western United States and includes the Sierra Nevada and the Coast Range in California.

- **Continental collisions**, in which both plates are carrying continental crust, have resulted in the formation of the Himalaya Mountains and the Tibetan Plateau. Continental collisions also formed many other mountain belts, including the Alps, Urals and Appalachians.
- Recent investigations indicate that **accretion**, a third mechanism of orogenesis, takes place where small crustal fragments collide and accrete to continental margins along plate boundaries. Many of the mountainous regions rimming the Pacific have formed in this manner. The accreted crustal blocks are referred to as terranes. The mountainous topography of Alaska and British Columbia formed as the result of the accretion of terranes to northwestern North America.
- Geologists are trying to determine what role plate tectonics and mountain building play in the origin and evolution of continents. At one extreme is the view that most continental crust was formed early in Earth's history and has simply been reworked by the processes of plate tectonics. An opposing view contends that the continents have gradually grown larger by accretion of material derived from the mantle.